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THE TRANSPORT OF GRAVEL IN AN EPHEMERAL SANDBED RIVER

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ABSTRACT

The channel dynamics of an ephemeral sandbed river, the Metsemotlhaba in southeast Botswana, were studied over a five year period using tagged magnetic particles of pebble and cobble size, scour chains and topographic cross-sections, with particular emphasis on the three-dimensional dispersal of gravels, patterns of scour and fill and depth of active layer. Two major flow events of equivalent magnitude occurred, moving the tagged particles, in December 1987, a mean distance of 837 m at a mean burial depth of 0·40 m, and in March 1991, a mean distance of 263 m at a mean burial depth of 0·39 m. The volume of mobile sediment, based on scour depth and distance of travel, was 2·7 times greater in the December 1987 event, in which the mean scour depth was almost twice the mean burial depth of the tagged particles. The distribution of distance of movement was asymmetrical in this first flood, when the tracer started from a surface location, but was monotonic thereafter. Intervening small to medium events yielded limited tracer movement with a mean burial depth equivalent to depth of scour.

The tracer moved in the low and transitional flow regimes. Burial depth distribution followed the gamma model. Field data confirm that longitudinal transport is independent of particle size and shape, and strongly skewed with respect to distance, whilst depths of scour in excess of 1 m for high magnitude events suggest that scour values predicted from the empirical equation of Leopold *et al.* underestimate by an order of magnitude. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: flow regime; tracers; sandbed river; gravel; scour and fill; sediment transport; sediment dispersion

INTRODUCTION

Pebbles and cobbles abound on the slopes alongside the banks of the Metsemotlhaba River in Botswana, a sand river typical of several major drainage networks in semi-arid Southern Africa. Large clasts, however, are rare in the riverbed, raising questions as to their fate in this environment. Assuming that the sediment of the river reflects the current hydroclimatic regime and catchment response, the river must dispose of the larger particles in a relatively efficient way. If it is found to be able to do so, how, and what is the process? Will it bury the coarse material under advancing sand dunes, gradually burying them deeper and deeper with increasing dune sizes contingent upon the incidence of floods of a longer and longer recurrence interval? Will some of the larger particles be evacuated far downstream by virtue of 'overpassing' (e.g. Raudkivi and Ettema, 1982), even more than by intermittent burial? On the other hand, if the sand bodies of the Metsemotlhaba (and similar rivers) represent fluvial conditions inherited from a previous hydroclimatic period, could the material be expected to stay, more or less, wherever placed? To answer these questions, we imposed on the well sorted sand of the riverbed a gravel tracer population of two sizes and monitored the tracer over five years.

From a more general viewpoint, the behaviour of tracer pebbles and cobbles in a sandy environment is of interest as an intrinsic fluvial process. It has the potential of opening up new avenues of evidence as to bed morphology changes during floods and the characteristics of dunes and other underwater bedforms generally

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obliterated by the flood recession. The problem of scour and fill during such floods is tied to these questions, and the evidence offered by the three-dimensional distribution of such tracers, coupled with additional tools such as scour chains, is of value in adding to the limited body of knowledge available.

BACKGROUND

The phenomena of scattered pebbles and cobbles on the surface of sandbed rivers, or as gravel lenses in the mobile layer or in the stratigraphic column, are well known in modern and ancient sediments (e.g. McKee *et al.*, 1967; McGowen and Garner, 1970; Jackson, 1976). It has been assumed that stream sediments are adjusted to hydraulic conditions and flow competence. However, sediment texture also depends on the range of grain sizes supplied to the channel from upstream tributaries, adjacent slopes and channel banks that may lack the largest sizes. Therefore, the maximum size of the sediment does not necessarily represent the maximum transporting power of floods (McKee *et al.*, 1967).

Fahnestock and Haushild (1962) conducted the first reported flume experiment on the movement of gravel on sand. Downstream displacement of individual stones occurred only during the upper plane bed, standing wave or antidune regimes. Flume experiments conducted by Hooke (1968) showed that the presence of coarse sand and granules in the bed generally results in sediment discharges that are lower than those found in comparable streams flowing over finer or more uniform material. Only in the flat bed flow regime are sediment discharges higher over the mixed bed. Hooke (1968) reported that small pebbles moved from one dune trough to another, armoured the troughs, and decreased sediment discharge.

Iseya and Ikeda (1987) examined short-term variations in bedload transport rates under a variety of bed conditions. Their tracer experiments showed that both sand and gravels move at a wide range of velocities. When gravel content is less than 50 per cent, the bed state is smooth and the velocity of the moving gravel particles is higher than that of the sand (Iseya and Ikeda, 1987; Ikeda and Iseya, 1988). Discharges required to move the gravel–sand mixture are nearly equal to those needed to transport the sand in the mixture (Ikeda and Iseya, 1988; Wilcock, pers. comm.). This indicates that gravel particles in a mixture with more than 50 per cent sand have little effect on the mobility of the mixture.

From the mid-1950s to the early 1960s, Leopold *et al.* (1966) conducted a tracer programme in gravel-bearing sandbed streams in New Mexico. To our knowledge, this is the only field study which has examined the movement of gravels in sand streams. It is unique in its long duration of observation (about five years) and in its combined use of several interdependent methods relevant to the tracer dispersal such as scour chains, recurrent cross-section surveys and associated geomorphic observations. Leopold *et al.* (1966) arrived at several important findings, some of them surprising.

First, they found that size does not affect longitudinal translation, as all particle sizes, when grouped into categories, move approximately the same distances when subjected to a flood. The Frijoles (Leopold *et al.*, 1966) experiment used gravel sizes that spanned nearly three orders of magnitude in weight, from particles 200 g upwards. Because of the limitations of the method used – painting the tracers, labelling them by number and retrieving them visually – smaller particles could not be used. In our experiment we have been able to extend the size range tested another order of magnitude downwards, with particles weighing 15 g forming the bulk of our tracers.

One of the most surprising results of the Leopold *et al.* (1966) study was the *en bloc* pattern of the longitudinal translation of the gravel particles, which they attributed, at least in part, to a kinematic wave effect (see also Langbein and Leopold, 1968). They found, especially in large flood events, that the retrieved tracer particles seemed to have moved downstream more *en masse* than according to any other predicted longitudinal distribution. Lacking a technique to retrieve buried tracers, Leopold *et al.* (1966) assumed that the surficial part of the population represented also the buried population. In this study we intend not only to verify the *en masse* character of the longitudinal dispersal, but also to check Leopold *et al.*'s (1966) assumption regarding the representability of the surface tracer population with the aid of the magnetic tracers we used.

Finally, Leopold *et al.* (1966) proposed a simple relationship between the average transport distance of coarse particles in a sand stream and a discharge parameter. While their function does not seem to have a high

correlation coefficient with the relatively widely variable data, its importance, in particular with regard to using it as a tool in discharge reconstruction based on long-term tracer distribution, justifies an attempt to strengthen this relationship by another experiment.

Many studies have examined the movement of sand particles and the development of bedforms in a sandbed flume in relation to flow regime (e.g. Simons and Richardson, 1960, 1961; Colby, 1964, Culbertson and Dawdy, 1964; Simons *et al.*, 1965; Nordin and Rathbun, 1970). Radioactive tracers were used to examine the vertical dispersion of sand-size particles in natural rivers (e.g. Hubbell and Sayre, 1964; Rathbun and Kennedy, 1978) as well as in flumes (Sayre and Hubbell, 1965; Crickmore and Lean, 1962a,b). Hubbell and Sayre concluded that the vertical distribution of the tagged particles is uniform through the mobile layer. Crickmore and Lean (1962a,b), Lean (1965) and Galvin (1965) reported a vertical gradient in the burial depth of particles.

For a high flow event, the bed scour during the rising stage and during the waning of the flood returns to approximately the initial mean bed elevation by filling (e.g. Leopold *et al.*, 1964). Assuming a uniform scour depth, Leopold and Maddock (1953) calculated the sediment discharge using depth of scour and mean sediment velocity. However, measurements of sediment accumulation in reservoirs showed that the maximum annual volume deposited was much smaller than that estimated using average values of scour and mean velocity (Lane and Borland, 1954). To explain this discrepancy, Lane and Borland (1954) hypothesized scour at flood crest in the narrow reaches and simultaneous fill in wide reaches farther downstream; the opposite was supposed to be true during the falling stage. Colby (1964) suggested that the maximum scour measured at a chain section is caused by the deepest antidune trough to pass during a flood. Observations by Culbertson and Dawdy (1964) supported Colby's hypothesis. Foley (1975, 1978) conducted combined field and flume experiments to determine the relative magnitude of scour and fill in steep, sandbed ephemeral streams. His estimates of antidune amplitudes indicated that scour and fill values measured by the scour chains could have been caused by bedform migration.

The present study extends the field experiments of Leopold *et al.* (1966) to use tracers of a different dimension in a sandbed river of greater bed depth and lower gradient. The data can be used to test the conclusions of the theoretical and laboratory flume-based studies that have been outlined in this review.

STUDY SITE

The Metsemotlhaba River forms part of the Limpopo network draining a part of the African continental divide region eastwards across the African Planation Surface (Shaw *et al.*, 1995). At the Botswana Department of Water Affairs gauge at Thamaga, 8 km downstream of the study site, the river drains a 615 km^2 asymmetrical catchment (Figure 1a). In the east and south, the catchment lies on highly resistant quartzites and sandstone. The western tributaries drain the border of the Kalahari sand across a granite landscape, which forms a typical etchplain surface of hill massifs, inselbergs and tors.

The study reach, 1400 m long, 20–40 m wide, and with an average longitudinal slope of 0·00215, lies between the villages of Thamaga and Moshupa (Figure 1a). The reach consists of flat areas, some weakly developed point bars, and a stable island (Figure 1b). The sand body, bounded by predominantly clay–silt steep banks 1–3 m high, is composed of well sorted and stratified sand that ranges between 2 and 5 m in depth (Wikner, 1980; Nord, 1985). The median grain size of the bed surface material is about 0·7 mm, and does not change with depth (Figure 2). Small pebbles are scattered on the bed surface and throughout the sand body. Lenses of small pebbles (up to 32 mm in size) and coarse sand were encountered in excavations up to 1 m deep.

According to the Botswana Department of Water Affairs gauge 2421 at Thamaga (Figure 1a), flow is ephemeral with an average of three to five discrete events per year. A rough estimate based on the 15 year long Thamaga record and adjusted for the smaller area at the study reach yields a mean annual peak discharge of 25 $m^3 s^{-1}$. Peak discharges of 60 $m^3 s^{-1}$ and over 100 $m^3 s^{-1}$ have a recurrence interval of about six and 14 years, respectively. During the rainy season (October to March) the water table rises to the bed surface and there may be uninterrupted flow for up to four weeks.

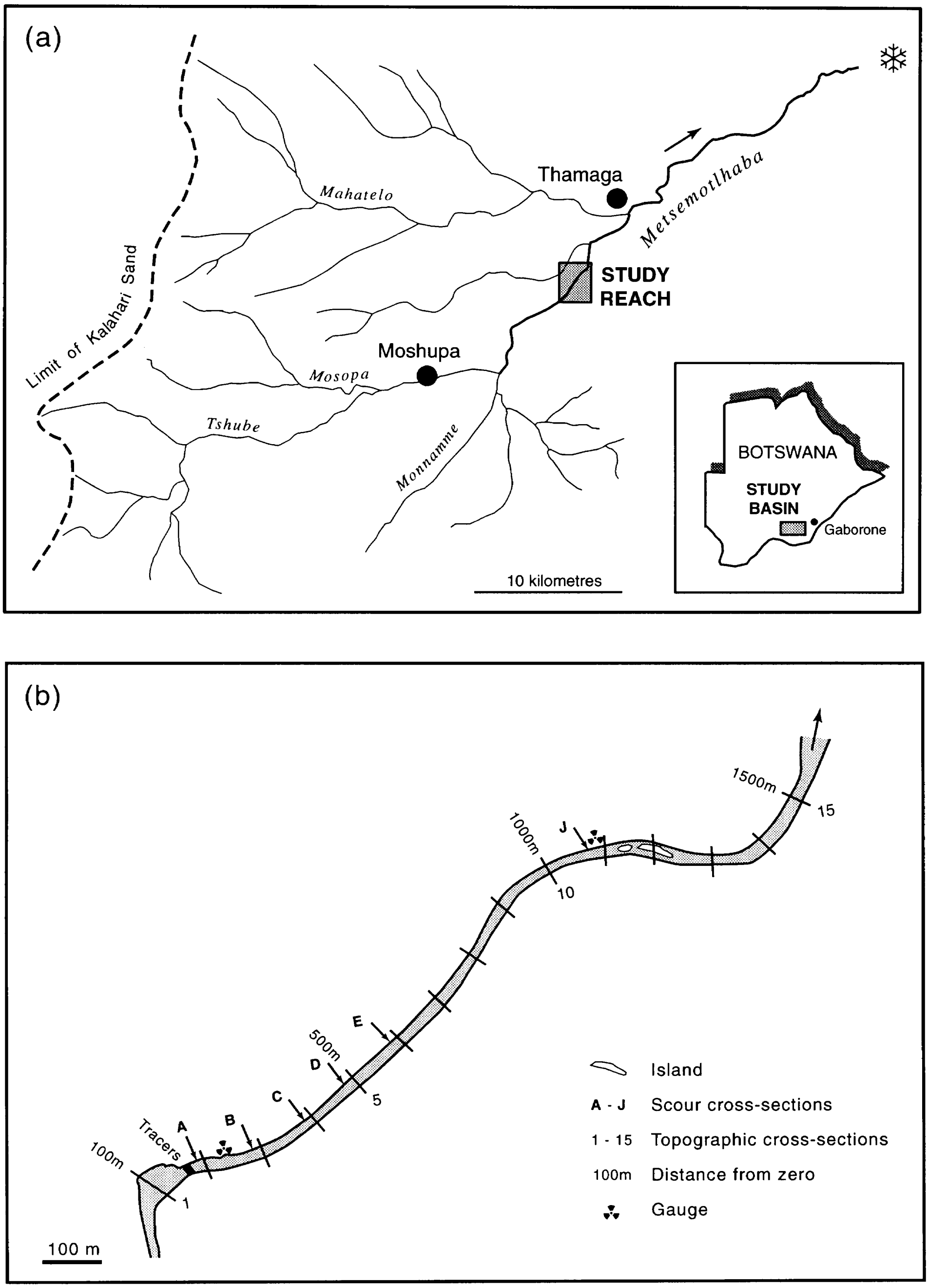

Figure 1. Location map of (a) the Metsemotlhaba River basin and (b) the study reach and instrumentation

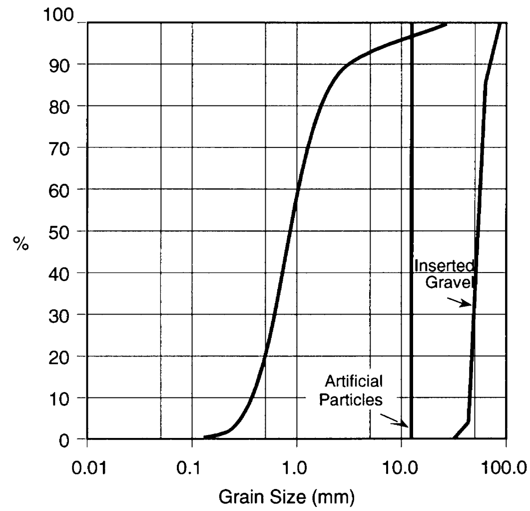

Figure 2. Particle size distribution of the Metsemotlhaba channel bed material and of the labelled particles. The gradation curve for the bed material is developed using 40 samples taken along the study reach

STUDY DESIGN

A total of 765 magnetically tagged particles (Hassan *et al.*, 1984) were placed in the streambed of the Metsemotlhaba River in August 1987. Of these, 610 were small (32·5 × 18·5 × 14·0 mm) synthetic magnetized pebbles of an ellipsoid shape weighing approximately 15 g each. The remaining particles (155) were large natural limestone pebbles between 90 and 600 g in weight (average 265 g) and between 47 and 90 mm in size (*b*-axis). The median sizes of the natural and synthetic tagged pebble are *c.* 65 and 23 times that of the bed material (Figure 2). A comparison of the tagged pebbles with the coarse fraction found in the bed indicates that the median size of the synthetic particles was about D_{97} of the bed material; the natural tagged pebbles are *c.* four times that of the largest particles found in the bed (Figure 2).

The tagged particles were positioned on the bed surface along three lines which extended from bank to bank orthogonally to the thalweg (Figure 1b). The lines were 1 m apart, and the tagged particles were placed along them at equal distances. The number of tagged particles used is very small relative to the channel area, and should not alter the bed roughness.

The tagged particles were recovered after every flood season with the aid of a magnet detector (Hassan *et al.*, 1984). Attempts to recover them after every individual flow event failed because the rise of the water table to the bed surface made excavation work impossible. Therefore, the data reported are the overall distance of movement and burial depth after each season. The tagged particles were recovered along a 2·5 km reach downstream of the tracer injection site (Figure 1b) with a detector whose sensitivity allowed recovery down to a maximum depth of 1 m. Upon careful recovery, preferably by digging from the side and recording the particle number, the tagged particle was reinserted into its ‘natural’ position. During the study period (1987–1991), 15 flow events occurred in the Metsemotlhaba, of which two were larger than 50 $m^3 s^{-1}$. Table I presents a summary of flow events and sediment movement.

Scour chains (Leopold *et al.*, 1966) were installed, 1 m deep, along six cross-sections. Each section included 10 or 11 chains spaced 2 m apart. In addition, 15 topographic cross-sections, spaced along 1400 m of the channel, were repeatedly surveyed (Figure 1b).

Table I. Summary of peak discharge and sediment transport

Event	Qmax (m^3s^{-1})	% moved recovered particles	Mean travel distance (m)		Mean burial depth (cm)		Mean scour (cm)	Mean fill (cm)	Computed mean scour (cm)*
			All particles	Moved only	All Particles	Moved only			
22 Dec. 1987	97								
8 Jan. 1988	1·3								
11 Feb. 1988	40								
3 Mar. 1988	50								
11 Mar. 1988	30								
87/88 season		99	842	837	40	40	>100†	72†	25
21 Oct. 1988	17								
9 Jan. 1989	30								
2 Feb. 1989	8								
88/89 season		23	82	19	41	36	37	36	12
7 Oct. 1989	24								
26 Nov. 1989	18								
8 Dec. 1989	11								
89/90 season		32	13	4	41	23	24	23	11
7 Jan. 1991	11								
29 Jan. 1991	12								
15 Feb. 1991	10								
17 Mar. 1991	90								
90/91 season		85	310	263	43	39	130‡	45	22

* Calculated for the peak discharge recorded through the season
† Based on section J only; the remaining scour chains were uprooted and minimum scour depth exceeded 100 cm
‡ Estimated using Kennedy's method (Foley, 1975)

RESULTS

Field observations

The first event after the placement of the tagged particles (December 1987) was large (recurrence interval >14 years) and was followed by a period of a high water table which persisted until the subsequent, moderate February flows (recurrence interval <four years). At the end of the season (September 1988) not a single particle was found on the channel surface. During the first event the tagged particles start moving from artificial less constrained positions than undisturbed particles in the surrounding bed. Therefore, we might expect the particle displacement to be higher in the first event than during subsequent events. However, our seasonal results are the combined movement of more than one flow event and therefore the impact of the first event should be minimal. The recovery rate was low (28 per cent), probably due to burial depth beyond the sensitivity of the magnetic locator. The low recovery rate implies that the burial depth distributions are truncated at depth. The vicinity of the island at $L = 1100$ m was found to be a preferred depositional area for the recovered particles (Figure 1b), while some were scattered throughout the study reach (Hassan *et al.*, 1995). The location of the tagged particles did not change significantly during the 1988/89 and 1989/90 seasons, as flows were of low magnitude and most particles did not move. The second major event occurred in March 1991, during which 80 per cent of the previously recovered tagged particles moved (Table I). Despite the event magnitude, which approached that of the December 1987 event, about 20 per cent of the previously located particles remained immobile (stationary).

Froude number calculations for peak flow discharges ranging between 1 m^3s^{-1} and 30 m^3s^{-1} yielded values from 0·2 to 0·35. Under these conditions flow is in the lower regime and dunes should be the dominant bedform in the channel (Simons *et al.*, 1965). Field observations show that during low flows (water depth less than 15 cm), small ripples developed (Figure 3A), with coarse sand and small gravels in the troughs. In some areas lobes of sediment, a few centimetres thick, were observed advancing downstream. On the other hand,

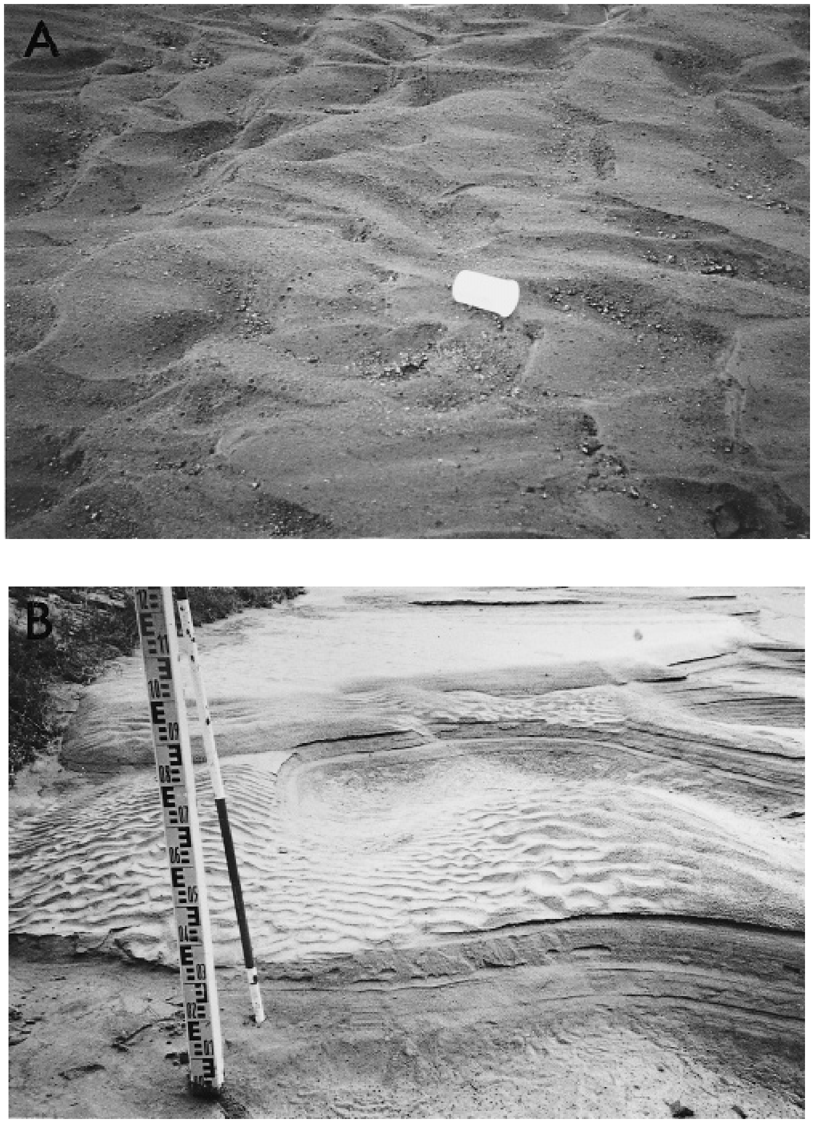

Figure 3. The February 1988 floods: (A) ripples developed toward the end of the flood and (B) preserved dunes on a point bar

dunes with amplitude of 30 cm were observed in the field at a flow discharge of about 8 $m^3 s^{-1}$. Figure 3B shows sand dunes preserved after the February 1988 events. For discharges greater than 30 $m^3 s^{-1}$, the Froude number, estimated using the Manning equation ($0{\cdot}02 < n < 0{\cdot}035$), was found to range between 0·35 and 0·7; the upper limit is close to the transition between the lower and the upper flow regimes (Simons and Senturk, 1992). The above calculations are based on the average flow velocity and one should expect a higher Froude number close to the channel centre. Field observations showed that the tagged particles moved over a wide range of flow conditions. Some particles, buried close to the bed surface, moved during relatively small events (less than 20 $m^3 s^{-1}$ – lower flow regime). It seems that during small events, particles moved in the lower plane bed regime in association with small dunes. Bed material samples taken from dune crests and troughs at a discharge of 8 $m^3 s^{-1}$ indicate that less than 1 per cent of the material at the crest is larger than 2 mm compared to approximately 20 per cent in the troughs. In the troughs, particles up to 32 mm were found.

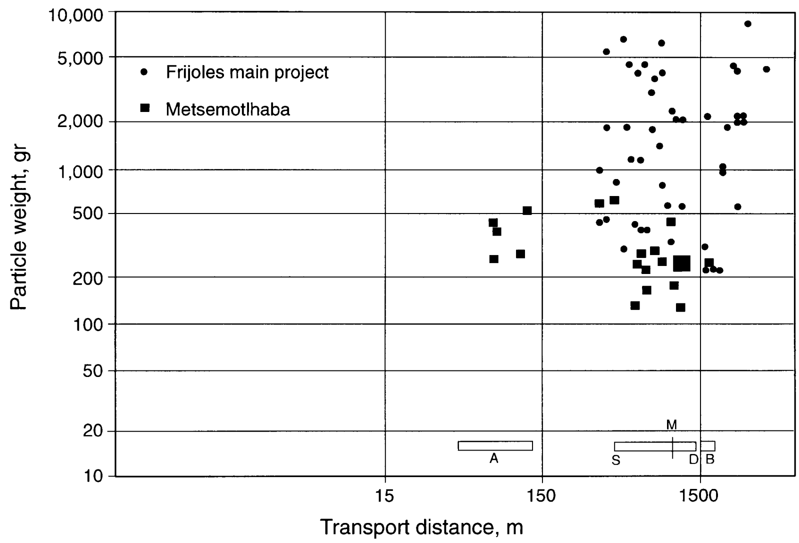

Figure 4. Travel distance of particles and weight, Metsemotlhaba and Frijoles. M = mean, SD = one standard deviation, A = 5 per cent of articles with smallest distance, and B = 5 per cent of particles with largest distance

Table II. Comparative data for the Frijoles and Metsemotlhaba rivers used in Figure 4

Event	Frijoles 13 September 1958	Metsemotlhaba 22 October 1987
Peak discharge ($m^3 s^{-1}$)	87	100
Unit discharge ($m^2 s^{-1}$)	3·6	4·4
Slope	0·019	0·00215
Median grain size (mm)	0·72	0·80

Distance of movement

Figure 4 presents the transport distance of data from Frijoles Main Project Reach (Leopold *et al.*, 1966) and relates, by comparison, the large limestone particles of this study moved by the 1987/88 events (i.e. mainly by the 22–24 December 1987 flood) to their weight. Comparative data are given in Table II. The pattern suggests that most of these particles moved more or less the same distance. A similar result was obtained in the Frijoles Main Project Reach for the 13 September 1958 flood (Figure 4), which had nearly identical discharge characteristics and channel width to the present study reach. However, one difference is noteworthy: though the background sand sizes of the channel bed were identical in both cases, the slope of the Metsemotlhaba is an order of magnitude less than that of Arroyo de los Frijoles at the Main Reach site. The Metsemotlhaba data show about a quarter of the traced particles whose distance of travel averages roughly 10 per cent of the distance moved by the rest, perhaps creating a discrete secondary wave. A similar disaggregation of the large tracer particles is not present in the Frijoles Main Reach, but is suggested by the Frijoles Locust Tree Reach data for the 14 July 1960 flood (Leopold *et al.* 1966, fig. 155, p. 217). The relatively small unit discharge of that flood may have been the trigger for the disaggregation of the coarse sediment 'wave' (Langbein and Leopold 1968).

The relation between distance of movement and particle size was examined after every flood season. The distance of travel varied substantially between particles, as well as between flood seasons. Particles of the same size, shape and roundness yielded a wide range of distances of travel (Hassan *et al.*, 1995). The

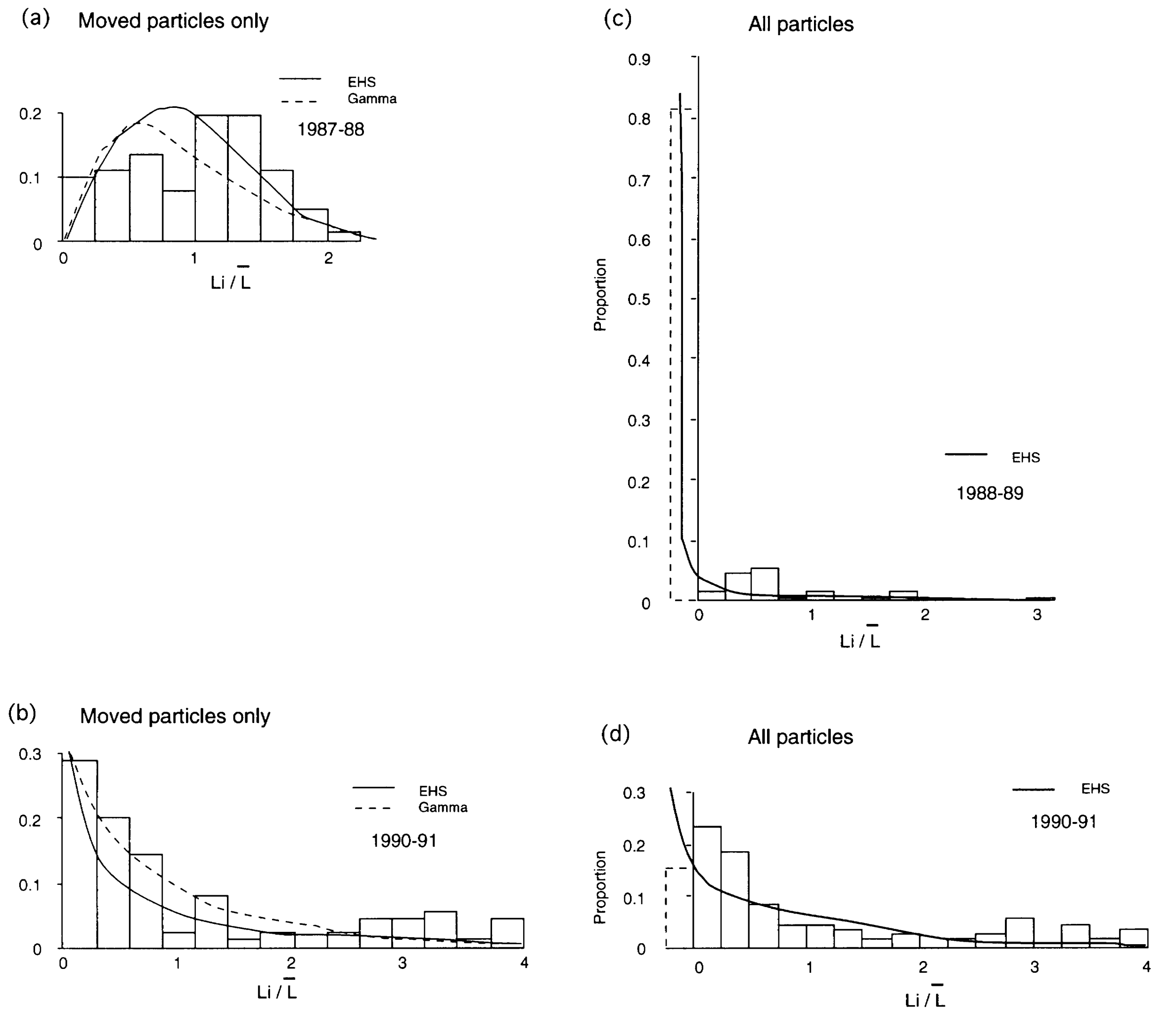

Figure 5. Downstream particle displacement of moved and all particles including those that remained stationary throughout the season. The dashed portion of the histogram represents stationary particles. The data were scaled by dividing the travel distance of each individual particle by the mean of the season. The scaled data were grouped for intervals of 0·25 of the mean travel distance for the season

distribution of distances of movement of the particles was examined. The data were evaluated in relation to the Einstein–Hubbell–Sayre (E-S-H) and gamma models (Einstein, 1937; Hubbell and Sayre, 1964; Hassan *et al.*, 1991). The physical and statistical explanation for the use of the models and the distinction between moved and all particles are explained in Hassan *et al.* (1991) and Hassan and Church (1992). Because of the lack of relation between distance of travel and particle size, we treated all sizes as a single group.

Two typical types of results are presented in Figure 5: (1) two cases of moved particles only; and (2) two cases of all particles, including stationary ones. In the case of the moved particles we used both models; only the E-S-H model was applied in the case of all particles. The similarity between the observed and fitted distributions was examined using the chi square test at the $\alpha = 0{\cdot}1$ level.

One large and two moderate events (Table I) occurred during the 1987/88 season. Therefore, the distribution of particle displacements represents the lumped behaviour of more than one event. The overall

distribution of moved particles after the 1988 season is shown in Figure 5a. All particles started from the bed surface, i.e. from fully exposed positions. Neither the E-H-S nor the gamma model describes the observed data satisfactorily. However, the observed distribution seems to be more uniform than skewed.

During the flood season of 1990/91 one large and three small events occurred (Table I). Since very little sediment moved during small events, we attribute most of the particle displacement and sediment transport to the single large event, which had an overriding impact on the mobility of the tagged particles. During the 1991 season, all of the moved particles started from a buried position, some relatively deep. Monotonic distributions were obtained and both models fit the data well (Figure 5b). In addition, a minor secondary mode is evident. The relatively short distance of movement during the March 1991 event (in contrast to the December 1987, dominant event, Table I) and the resulting distribution of particle displacements can be attributed to the buried starting position of the particles.

The downstream displacements of all particles, including those that remained stationary throughout the season, were evaluated using the E-H-S model (Figure 5c and d). The large number of stationary particles dominates the overall distribution during the 1988/89 season. For this season, the E-H-S model and the observed data yielded similar monotonic distributions. For the 1990/91 season, the E-H-S model yielded a monotonic curve while a skewed peak distribution was obtained for the field data (Figure 5d). For both cases, the chi square test indicates that the fitted model does not describe the data satisfactorily.

Burial depth

The applicability of vertical mixing models developed for sand and gravel-bed rivers to gravels imposed on sandbed rivers depends on the nature of movement and the process by which gravels are buried by sand. Flume experiments (e.g. Fahnestock and Haushild, 1962; Simons and Senturk, 1992) showed that gravels on sandbed rivers are likely to be embedded and buried by advancing sediment. Here the relation between burial depth and particle size was examined using available data and reported on the basis of the overall seasonal distributions. Obviously, these depend not only on the number of events per season, but also on their magnitude.

Several distribution functions (e.g. gauss, gamma) were tried, and it was found that a gamma distribution best describes the burial depth data. Two examples of the burial depth distributions of particles moved during the events are presented in Figure 6a and b. The burial depth distribution of particles moved by the 1987/88 floods, the first after the placement of the tagged particles is presented in Figure 6a. During this season, one large and two moderate events occurred and the particles probably moved several times, especially the shallow-buried particles. The distribution is positively skewed and has a relatively wide peak (Figure 6a). The burial depth distribution of particles moved by the 1990/91 floods (Table I) represents the vertical behaviour of particles during relatively large events (Figure 6b). The figure shows that a gamma distribution fits the data well.

Two typical examples of the overall distribution of all particles, including those that remained stationary throughout the season, are presented in Figure 6c and d. Most of the tagged particles did not move during the 1988/89 and 1989/90 flood seasons and the distribution is dominated by the stationary particles. The figure shows that the burial depth distribution for the large event of 1990/91 has a skewed peak which indicates that some particles were deeply buried.

Scour and fill

The scour and fill data of the chains are summarized in Table I. During 1987/88 and 1990/91 most of the chains in the five upstream sections (Figure 1b) were uprooted and not retrieved. This implies that the scour depth exceeded 1 m during the large events. Only section J (Figure 1b) had most of the chains preserved; they show scour and fill in the order of 50–100 cm during 1987/88. At the end of that season, new ones replaced all uprooted chains, and those that remained were reset to a completely vertical position. For 1988/89 the maximum scour and fill was recorded in section B. In this section the scour depth ranged from 3 cm near the left bank to 68 cm near the right bank. The mean scour and fill for the study reach were similar (Table I). Due to high water table only chains in sections A and D were retrieved at the end of the 1989/90 season and the

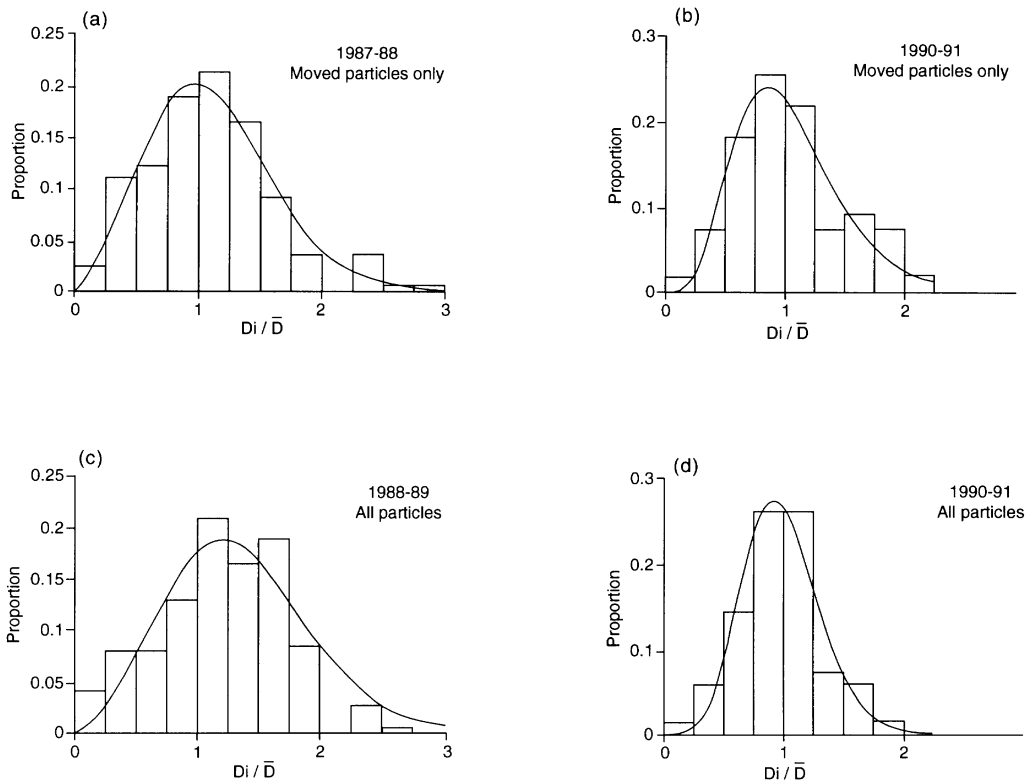

Figure 6. Burial depth distribution of moved and all particles. The data were scaled by dividing the burial depth of each individual particle by the mean of the season. Then the scaled data were grouped by intervals equal to 0·25 of the mean burial depth of the season

mean scour and fill were found to be similar. Although the mean scour and fill for 1988/89 were larger than those of 1989/90, they have about the same range. During 1990/91, a mean fill of 45 cm and more than 100 cm of scour were observed. The data indicate that the scour and fill changes between sections as well as between flood seasons.

Figure 7 presents scour, fill and net changes at sections J and A over two successive seasons. During the major events of the 1987/88 season, the scour depths were about the same along section J, while most of the fill occurred near the right bank. The overall changes in bed elevation indicate a net scour especially near the left bank. A different pattern was obtained for the small events of 1988/89 with the deepest scour located in the channel centre and the shallow parts near the left bank. A different pattern was obtained for section A, a net fill during the 1987/88 season and net scour during the 1989/90 season.

The scour depth distribution reflects changes in the bedform amplitudes during a given flow event and over the study reach. The distribution of the depth of scour and fill has been examined for the complete set of the 1988/89 data. The data were grouped into intervals equal to 0·25 of the mean scour and fill. Figure 8 presents the scour and fill distribution. In accordance with the burial depth distribution and the distribution of bedform amplitude (Paola and Borgman, 1991), we chose to fit a two-parameter gamma function. For the Metsemotlhaba, the analysis yielded a skewed-peak distribution for both the scour and fill. Chi square test indicates that the fitted and the measured curves are similar.

During the 1987/88 season the mean burial depth of moved particles (Table I) was about half of the mean scour and fill as recorded in section J (Figure 1b). In the two subsequent years the means of burial depth, scour and fill were about the same. During the 1990/91 season the means of burial depth of moved particles and of

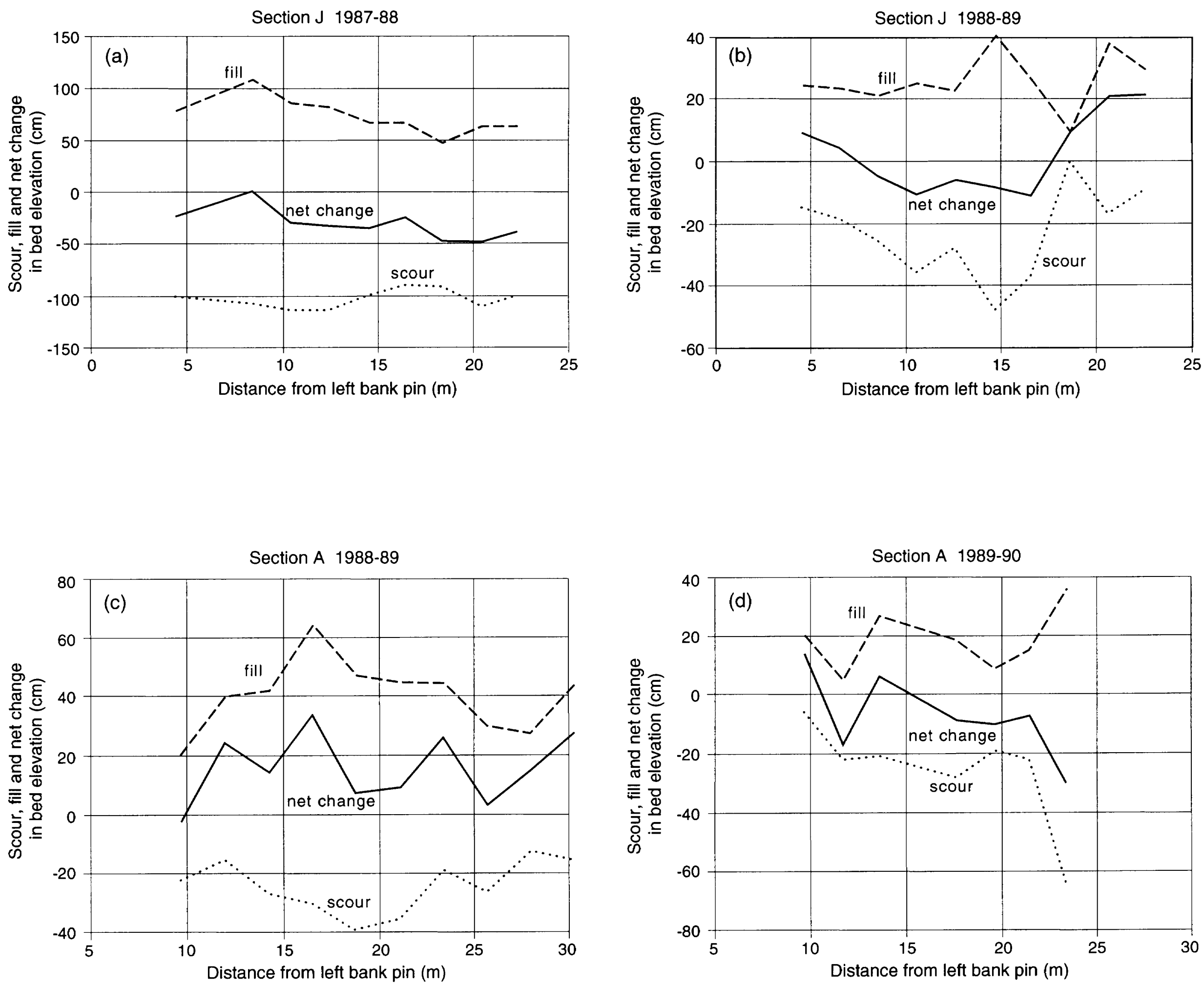

Figure 7. Scour, fill and net change at sections A and J during two flood seasons

fill were about the same and about half that of the mean scour. It seems that during high flow events (1987/88 and 1990/91), burial occurs throughout the fill phase so that burial depths are distributed over the range of maximum fill. However, the relatively low mean burial depth could be due to the loss, during a large event, of most of the buried tracers beyond the detector range, so that the observed mean depth may be biased on the low side. In this case the mean burial depth does not represent the depth of the scour layer. During low flow events (1988/89 and 1989/90) the mean burial depth approaches that of the maximum scour depth; in this case the mean burial depth is representative of the depth of the active layer.

Using relations between flow conditions and bedform characteristics (for dunes and antidunes–related in sand rivers to depth of scour), as developed by Kennedy (1963) and applied by Foley (1977, 1978), the depth of scour for the large events can be estimated. Calculation for the two largest events recorded over the study periods yields a maximum scour depth of about 130 cm – a result in agreement with the $> 1{\cdot}0$ m scour depth recorded in the upper part of the study site (Table I).

A comparison between the measured and predicted scour values using the Leopold *et al.* (1966) empirical equation is presented in Table I. The depth of scour was calculated for our study site using the maximum peak

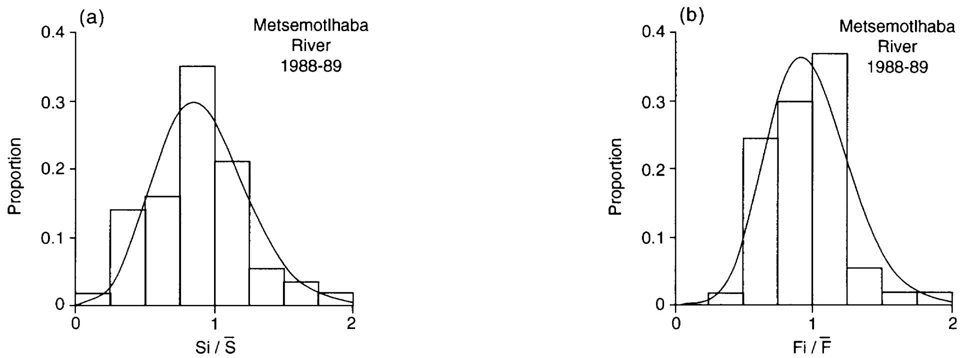

Figure 8. Distribution of scour and fill depths based on data from the Metsemotlhaba river. The data were scaled by dividing the scour/fill depth of each scour chain by the mean of the reach. Then the scaled data were grouped by intervals equal to 0·25 of the mean scour/fill depth of the reach (Si = scour depth; $\bar{S}$ = mean scour depth; Fi = fill depth; $\bar{F}$ = mean fill depth)

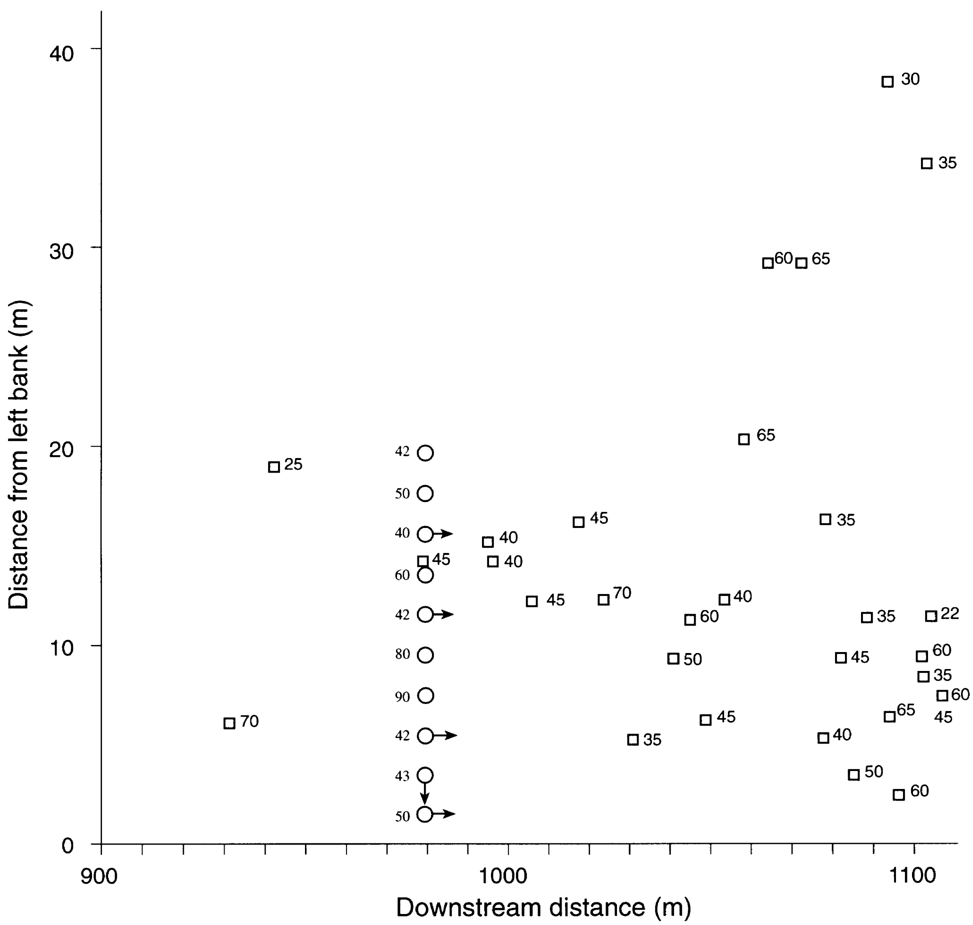

Figure 9. The three-dimensional dispersion of tagged particles as found after the 1990/91 season. Scour chain data at section J are shown for comparison. Arrows show the direction and the way that the chains were recovered in the field. The numbers besides the tagged particles and the scour chains indicate the depth of burial and scour (in cm), respectively

discharge recorded during the season and yields estimates at least one order of magnitude lower than our field data.

Particle burial and scour chains

The correspondence of information derived from the retrieval of buried tracer particles with the depth of scour as indicated by chains (Leopold *et al.*, 1966) is important in the evaluation of the mechanism of the flow which caused the tracer dispersal and the chain elbowing. The simplest assumption is that the chain's final elbow, as subsequently uncovered, occurs at the flow peak with the highest streampower, and that the large tracers begin to settle at about the same time, with the onset of the declining flow. Whether they continue to settle far into the flow recession, in tandem with bed-wave amplitude changes to approximately the pre-flood level, is not known.

Figure 9 offers an important insight into this problem. It shows the three-dimensional distribution of the tracer particles as found after the 1990/91 flood season in relation to the scour chain data as recorded at section J, located at station 980 of the study reach (Figure 1b). Included in the sketch are all recovered particles within a distance of 100 m downstream and upstream of the scour chain section. Here, we concentrate on the high degree of correspondence between the 'elbow' depth of the chains and the burial depth of tracers. The subreach upstream of section J had few deposited tracers, but these were abundant further downstream, with depth distributions similar to those of the 'elbow' depths of the section J chains. The arrows in the figure show the direction and the way that the chains were found in the field. One tracer retrieved from a depth of 45 cm was located 1 m from a chain whose 'elbow' was at 40 cm. Two additional tracers were found buried under 40 cm of sand less than 20 m downstream on continuing flow lines. While the implications of the settling pace of the large particles during the recession and its relation to the depositing sand will be discussed in another section, it is clear from the comparison enabled by Figure 9 that at least the maximum depth values of the tracers, and perhaps the majority of these, provide values of scour depth similar to those derived from the scour chains (whereas we infer that they are maximum).

Particle situation and distance of movement

The entrainment of a particle depends on its depth within the active layer. A buried particle can move only if scour exposes it to the flow. Deeply buried particles are likely to move close to the peak flows of moderate to large events and thus will be exposed to a relatively high stream power. In addition, flow duration plays a major role in controlling the distance of movement of exposed particles. The influence of burial depth on the distance of movement of the tagged particles was examined. Particles were grouped into 10 cm intervals of burial depth antecedent to the flood season and the mean distance of movement was calculated. The data cover a wide range of flow events; therefore, the mean distance of movement of each burial depth subgroup was scaled using the mean distance of movement of all recovered particles (Figure 10).

Two types of data are presented: moved particles only (Figure 10a) and all particles including stationary ones (Figure 10b). Despite the scattered nature of the data, the figures show a general pattern of decline in the scaled mean distance with burial depth. This implies that particles found on or close to the bed surface are likely to move longer distances than those buried deep in the sand body.

Downstream changes in burial depth

A downstream decline in the burial depth of sand grains on sandbed rivers was observed in the flume by Crickmore and Lean (1962a, b). In addition, Galvin's (1965) theoretical analyses of the dispersion of sediment from a trench supports the Crickmore and Lean conclusion.

Downstream changes in the burial depth of the tagged particles were examined using the 1988 data (Figure 11). Generally, a lack of relation between burial depth and downstream distance is indicated: some particles were transported long distances while others of the same burial depth moved relatively short distances. Although scatter is large, burial depth of the post-1988 tagged particles shows a general decline with distance (Figure 11).

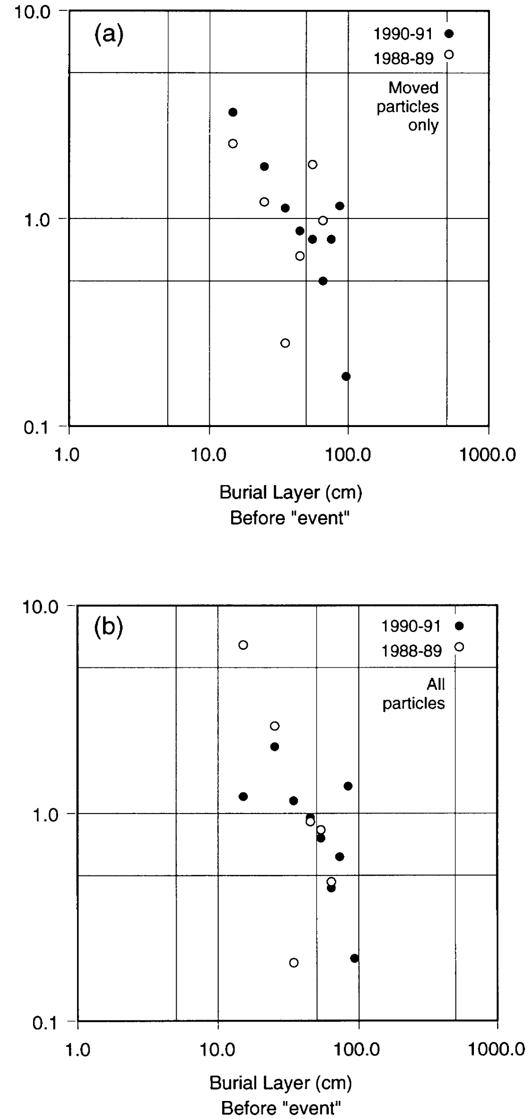

Figure 10. Relation between mean distance of movement and burial depth of particles classified according to their burial depth: (a) before the event – moved particles only; (b) before the event – all particles including those that remained stationary throughout the season

DISCUSSION AND SUMMARY

High rates of rise and fall of discharge characterize flash floods in arid and semi-arid regions and bedforms have a minimum relaxation time in which they are able to respond. Jones (1977) related the nature of the adjustment to bedform type and size that depends on the rate of change in discharge. If the flow falls faster than the relaxation time, the bedforms stop moving and will be preserved in the river; the opposite is true in the case of gradual changes in flow. Accordingly, bedforms developed during flash floods at the study site of the Metsemotlhaba River may be left stranded after floods (Jones, 1977). Field inspection after floods revealed a flat bed with no bedforms, except small dunes preserved on a point bar after the February 1988

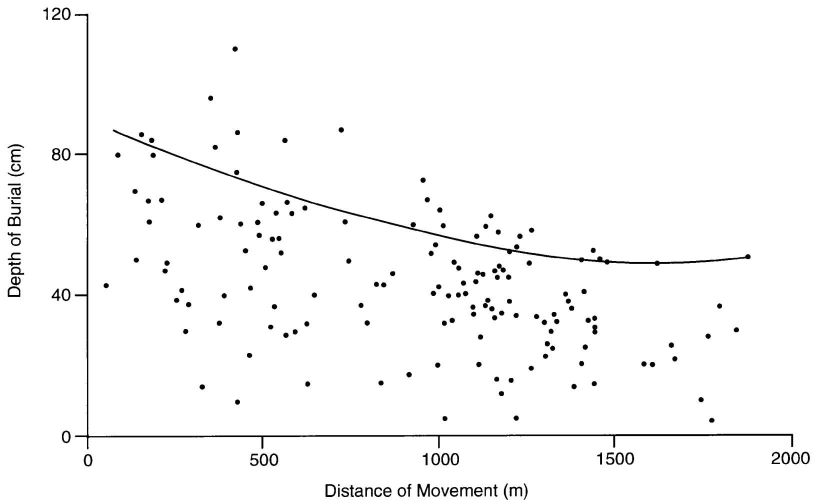

Figure 11. Relation between burial depth and distance of movement of individual particles after the 1987/88 season. The curve is developed using 200 m sections along the study reach. The burial depth of 80 per cent of the tagged particles found in the section is plotted

events. It seems that Jones's model is not applicable to the Metsemotlhaba, implying that the falling limb of the hydrographs were long enough to destroy the bedforms.

Froude number estimates for a wide range of discharges suggest that the tagged particles moved during the lower and transition flow regimes. It seems that during small events the tagged particles moved either over a plane bed before the development of dunes, or from one trough to another during the dune regime. The conditions of the movement of particles during high flows are not clear and there are a few possibilities: the first is overpassing from one trough to another during the dune regime, the second along certain path(s) between the dunes that cover most of the bed, and the third during the upper plane bed regime in the transition between the lower and upper flow regimes. The first possibility means that particles are likely to be buried by the advancing dunes and spread over a large area, while the second possibility implies concentration and deposition in preferred areas. Although the exact hydraulic conditions under which the tagged particles moved are not known, it is possible to conclude that the particles moved during the lower flow regime. The conclusion is based on flow regime calculations, described above, and on the fact that some of the tagged particles moved during low flows. This conclusion contradicts results from flume experiments (e.g. Fahnestock and Haushild, 1962) which indicated that the particles move during the upper regime only.

The spatial dispersion pattern of the tagged particles was dominated by the first flood, one of the two largest of the study period, and illustrates the influence of bed morphology on sediment transport. Large proportions of the particles were found in the vicinity of the island and in low point bars. Around the island, the mean channel width increases from about 25 m to 40 m and the channel gradient drops slightly. These changes in the hydraulic geometry, leading to reduced specific stream power, appear to be the main cause of the deposition of the particles in the area. Events that occurred during 1988/89 and 1989/90 were relatively small and most of the tagged particles did not move. The dispersion pattern of the moved particles before and after each of these two flood seasons was very similar.

The relation between travel distance and particle weight yielded results similar to those reported by Leopold *et al.* (1966). The lack of relation between distance and size and the concentration of the deposited particles in the 600–1200 m reach after the 1987/88 flood season suggest that particles deposited in preferred areas. The distributions of travel distances for several events were tested against the Einstein–Hubbell–Sayre and gamma models. For small and single events, both models yielded a monotonic distribution and the

measured data are similar to the fitted curves. In the case of a full season with large events, the fitted models and the observed data were different. It seems that during large events particles move a number of steps and from different vertical starting positions. In contrast, during small events the movement is likely to be random and both models are expected to yield good results. Similar results were obtained for gravel-bed rivers (Hassan and Church, 1992).

The large event of March 1991 was similar in both duration and magnitude to that of December 1987. According to the distribution of the moved tracers, the event yielded a monotonic longitudinal distribution similar to those obtained for small events. Data from scour chains indicated that during both large events the depth exceeded 1 m. In addition, the tracers in both events yielded a similar burial depth distribution. The main difference between the two events is in the starting positions of the tracers: in the 1987 event all particles started from the bed surface while the 1991 event had to contend with buried locations. The difference in the distance of movement between the two events demonstrates the relative importance of particle location on entrainment and duration of movement. In other words, particles located on or close to the bed surface are expected to move first and probably for a longer period of time than deeply buried ones.

We have found the burial depth of individual particles to vary without any relation to particle size. There are three possibilities whereby tagged gravels may become buried in sandbed rivers: (1) in the trough of advancing bedforms; (2) by sand which moves into suspension during high flows and settles during the falling limb of the flood; and (3) by movement in a traction carpet which, as it slows down, results in a quasi-simultaneous deposition of all clasts.

During small events the burial depth and vertical mixing of the tagged particles are dominated by the movement of wave-like bedforms and particle size has little effect, if any, on the processes. During high flows, on the other hand, alternation of the first two mechanisms is possible: deposition of suspended sediment followed by advancing bedforms during the falling limb of the hydrograph. The third mechanism is not likely to occur for the following reasons: (1) it is possible to find deeply buried gravels in the vicinity of others located near the bed surface, implying non-simultaneous deposition of particles; (2) that some buried particles remained stationary while others nearby were moved contradicts the notion of traction carpet; and (3) the decline in the mean distance of the tagged particles with burial depth.

The burial depth distribution depends mainly on the distribution of bedform amplitude and the magnitudes and duration of the flow events. Paola and Borgman (1991) showed that the topographical height of bedforms has a gamma distribution, thus burial depth data represent the local topography at the time of fill. Our observations confirm that the gamma model describes the data well, to the extent that burial depth data can be used to reconstruct the distribution of bed topography during a given event.

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